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# Semi-inclusive Deep Inelastic Electron Scattering off the Deuteron and the Neutron to Proton Structure Function Ratio [a]

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**Abstract**

The production of slow nucleons in semi-inclusive deep inelastic electron scattering off the deuteron is investigated in the region $x \gtrsim 0.3$. It is shown that within the spectator mechanism the semi-inclusive cross section exhibits a scaling property even at moderate values of $Q^2$ ($\sim$ few $(GeV/c)^2$) accessible at present facilities, like $CEBAF$. Such a scaling property can be used as a model-independent test of the dominance of the spectator mechanism itself and provides an interesting tool to investigate the neutron structure function. The possibility of extracting model-independent information on the neutron to proton structure function ratio from semi-inclusive experiments is illustrated. The application of the spectator scaling to semi-inclusive processes off complex nuclei is outlined.

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The investigation of deep inelastic scattering ($DIS$) of leptons off the nucleon is an important tool to get fundamental information on the nucleon wave function and the properties of its constituents. However, till now experimental information on the structure function of the neutron has been inferred from nuclear (usually deuteron) data by unfolding the neutron contribution from the inclusive nuclear cross section. Such a procedure, which typically involves the subtraction of both Fermi motion effects and contributions from different nuclear constituents (i.e., nucleons, mesons, isobars, ...), leads to non-trivial ambiguities related to the choice of the model used to describe the structure of the target and the mechanism of the reaction. As is well known, existing "experimental data" [1, 2] on the neutron structure function $F_2^n(x, Q^2)$ (where $x \equiv Q^2/2M\nu$ is the Bjorken scaling variable and $Q^2 = -q^2 = |\vec{q}|^2 - \nu^2 > 0$ is the squared four-momentum transfer) have been determined by combining deuteron, $F_2^D(x, Q^2)$, and proton, $F_2^p(x, Q^2)$, inclusive data. It turns out (see, e.g., [2]) that at $x \lesssim 0.65$ the values obtained for the neutron to proton structure function ratio, $R^{(n/p)}(x, Q^2) \equiv F_2^n(x, Q^2)/F_2^p(x, Q^2)$, are almost independent of the assumed (non-relativistic) deuteron wave function, whereas at larger values of $x$ there is a significant model dependence. In particular, at $x \simeq 0.85$ the sensitivity of the ratio $R^{(n/p)}(x, Q^2)$ to different deuteron wave functions corresponding to various realistic models of the nucleon-nucleon interaction, reaches $\sim 20\%$ [2]. Furthermore, corrections to the usual convolution formula arise when off-shell components of the deuteron wave function as well as off-mass-shell dependence of the nucleon structure function are taken into account [3]. A recent estimate of these corrections [4] suggests a ratio $R^{(n/p)}(x, Q^2)$ at $x \to 1$ significantly larger than the notorious "1/4" limiting value.

An alternative way to obtain information on the neutron structure function could be the investigation of semi-inclusive $DIS$ reactions of leptons off the deuteron ${}^2H(\ell, \ell' N)X$ (cf. [5]). The aim of this letter is to address few relevant questions concerning the semi-inclusive $DIS$ process ${}^2H(\ell, \ell' N)X$ at moderate and large values of $x$ ($x \gtrsim 0.3$) within the so-called spectator mechanism, according to which, after lepton interaction with a quark of a nucleon in the deuteron, the spectator nucleon is emitted because of recoil and detected in coincidence with the scattered lepton. It will be shown that the cross section corresponding to such a mechanism exhibits a scaling property (the spectator-scaling) even at moderate values of $Q^2$ ($\sim$ few $(GeV/c)^2$), which are accessible at present facilities, like, e.g., $CEBAF$. Such a scaling property can be used as a model-independent test of the dominance of the spectator mechanism itself and provides an interesting tool to extract the neutron structure function from semi-inclusive data. Moreover, in the spectator-scaling regime the neutron to proton structure function ratio $R^{(n/p)}(x, Q^2)$ can be obtained directly from the ratio of the semi-inclusive cross sections of the processes ${}^2H(e, e'p)X$ and ${}^2H(e, e'n)X$. Finally, the generalization of the spectator-scaling to semi-inclusive $DIS$ processes off complex nuclei of the type $A(\ell, \ell'(A-1)_{gr})X$, where, besides the scattered lepton, the residual $(A-1)$-nucleon system in its ground state is detected in the final state, will be outlined.

In case of electron scattering, the semi-inclusive cross section of the process ${}^2H(e, e'N)X$

reads as follows

$$\frac{d^4\sigma}{dE_{e'}\ d\Omega_{e'}\ dE_2\ d\Omega_2} = \sigma_{Mott}\ p_2\ E_2\ \sum_i\ V_i\ W_i^D(x, Q^2; \vec{p}_2) \tag{1}$$

where $E_e$ ($E_{e'}$) is the initial (final) energy of the electron; $i \equiv \{L, T, LT, TT\}$ identifies the different types of semi-inclusive response functions ($W_i^D$) of the deuteron, $\vec{p}_2$ is the momentum of the detected nucleon and $E_2 = \sqrt{M^2 + p_2^2}$ its energy ($p_2 \equiv |\vec{p}_2|$). In Eq. (1) $V_i$ is a kinematical factor, given explicitly by $V_L = Q^4/|\vec{q}|^4$, $V_T = tg^2(\theta_{e'}/2) + Q^2/2|\vec{q}|^2$, $V_{LT} = (Q^2/\sqrt{2}|\vec{q}|^2)\ \sqrt{tg^2(\theta_{e'}/2) + Q^2/|\vec{q}|^2}$ and $V_{TT} = Q^2/2|\vec{q}|^2$, where $\theta_{e'}$ is the electron scattering angle.

Let us consider the spectator mechanism, according to which the virtual photon is absorbed by a quark belonging to the nucleon $N_1$ in the deuteron and the recoiling nucleon $N_2$ is emitted and detected in coincidence with the scattered electron. Within the plane wave impulse approximation and assuming a non-relativistic deuteron wave function, the semi-inclusive deuteron response function $W_i^D$ is related to the structure function $W_\alpha^{N_1}$ of the struck nucleon by

$$W_i^D(x, Q^2; \vec{p}_2) = \frac{M}{E_2} n^{(D)}(p_2) \sum_{\alpha=1,2} C_i^\alpha(x, Q^2; \vec{p}_2)\ W_\alpha^{N_1}(M_1^*, Q^2) \tag{2}$$

where $n^{(D)}$ is the (non-relativistic) nucleon momentum distribution in the deuteron and $M_1^*$ is the invariant mass of the struck nucleon. Using the energy and momentum conservations, $M_1^*$ is explicitly given by $M_1^* = \sqrt{(\nu + M_D - E_2)^2 - (\vec{q} - \vec{p}_2)^2}$, where $M_D$ is the deuteron mass. The coefficients $C_i^\alpha(x, Q^2; \vec{p}_2)$, appearing in Eq. (2), depend upon the structure of the off-shell nucleonic tensor, $W_{\mu\nu}^{N_1,off}$, and different prescriptions for the latter exist in the literature (cf. [6]). In this letter we are mainly interested in the production of slow nucleons ($p_2 \lesssim 0.3\ GeV/c$) and, therefore, off-shell effects (being of relativistic origin) are not expected to play a relevant role. Let us consider for $W_{\mu\nu}^{N_1,off}$ the following choice (see [6])

$$W_{\mu\nu}^{N_1,off} = -W_1^{N_1}(M_1^*, Q^2)\left[g_{\mu\nu} + \frac{q_\mu q_\nu}{Q^2}\right] + \frac{W_2^{N_1}(M_1^*, Q^2)}{M^2}\tilde{k}_{1,\mu}^{off}\ \tilde{k}_{1,\nu}^{off} \tag{3}$$

where $W_\alpha^{N_1}(M_1, Q^2)$ is the on-shell nucleon structure function and $\tilde{k}_{1,\mu}^{off} \equiv k_{1,\mu}^{off} + q_\mu(k_1^{off} \cdot q)/Q^2$. The off-shell nucleon four-momentum is given by $k_1^{off} \equiv (k_{1,0}^{off}, \vec{k}_1) = (M_D - E_2, -\vec{p}_2)$, where the latter equality follows from energy and momentum conservations. In principle, the structure functions $W_\alpha^{N_1}$ appearing in Eq. (3) should depend not only on $M_1^*$ and $Q^2$, but also on $k_1^2 \equiv (M_D - E_2)^2 - p_2^2$. From Eq. (3) one has

$$\begin{aligned}
C_L^1 = -\frac{|\vec{q}|^2}{Q^2} \quad C_L^2 &= \frac{|\vec{q}|^4}{Q^4}\left[\frac{(M_D - E_2)|\vec{q}| + \nu p_2 cos(\theta_2)}{M|\vec{q}|}\right]^2 \\
C_T^1 = 2 \qquad C_T^2 &= \left(\frac{p_2 sin(\theta_2)}{M}\right)^2
\end{aligned}$$

$$C^1_{LT} = 0 \qquad C^2_{LT} = \frac{\sqrt{8} p_2 sin(\theta_2)}{M} \frac{|\vec{q}|^2}{Q^2} \frac{(M_D - E_2)|\vec{q}| + \nu p_2 cos(\theta_2)}{M|\vec{q}|} \, cos(\phi_2)$$

$$C^1_{TT} = 0 \qquad C^2_{TT} = \frac{1}{2} \left( \frac{p_2 sin(\theta_2)}{M} \right)^2 cos(2\phi_2) \tag{4}$$

where $\theta_2$ and $\phi_2$ are the azimuth and polar angles of $\vec{p}_2$ with respect to $\vec{q}$, respectively.

The relevant quantity, which will be discussed in this letter, is related to the semi-inclusive cross section (1) by

$$F^{(s.i.)}(x, Q^2; \vec{p}_2) \equiv \frac{1}{K} \, \frac{d^4\sigma}{dE_{e'} \, d\Omega_{e'} \, dE_2 \, d\Omega_2} \tag{5}$$

where $K$ is a trivial kinematical factor, given by $K \equiv \frac{2Mx^2 E_e E_{e'}}{\pi Q^2} \, \frac{4\pi\alpha^2}{Q^4} \, \left[1 - y + \frac{y^2}{2} + \frac{Q^2}{4E_e^2}\right]$, with $y \equiv \nu / E_e$. Eq. (5) can be expressed in terms of the structure function $F_2^{N_1}(x^*, Q^2)$ of the struck nucleon as

$$F^{(s.i.)}(x, Q^2; \vec{p}_2) = M \; p_2 \; n^{(D)}(p_2) \; \frac{F_2^{N_1}(x^*, Q^2)}{x^*} \; D^{N_1}(x, Q^2; \vec{p}_2) \tag{6}$$

where $x^* \equiv Q^2 / 2M\nu^*$, $\nu^* \equiv (Q^2 + M_1^{*2} - M^2)/2M$ and

$$D^{N_1}(x, Q^2; \vec{p}_2) = \frac{1 - y - Q^2/4E_e^2}{1 - y + y^2/2 + Q^2/4E_e^2} \frac{\nu^2}{\nu^{*2}} \; \sum_i \; V_i \; \left[ C_i^2 + C_i^1 \; \frac{1 + \nu^{*2}/Q^2}{1 + R_{L/T}^{N_1}(x^*, Q^2)} \right] \tag{7}$$

with $R_{L/T}^N$ being the ratio of the longitudinal to transverse cross section off the nucleon. Using Eq. (4) it can be easily checked that in the Bjorken limit (i.e., for $Q^2 \to \infty$ at fixed values of $x$ and $y$), the contributions from the interference terms ($i = LT$ and $i = TT$) are identically vanishing. Moreover, after considering $R_{L/T}^{N_1} \to_{Bj} 0$, the longitudinal term vanishes too and, finally, one has $D^{N_1} \to_{Bj} 1$, which implies $F^{(s.i.)}(x, Q^2; \vec{p}_2) \to_{Bj} M \; p_2 \; n^{(D)}(p_2) \; F_2^{N_1}(x^*)/x^*$, where $F_2^{N_1}(x^*)$ stands for the nucleon structure function in the Bjorken limit (apart from logarithmic $QCD$ corrections). It follows that in the Bjorken limit and at fixed values of $p_2$ the function $F^{(s.i.)}$ does not depend separately upon $x$ and the nucleon detection angle $\theta_2$, but only upon the variable $x^*$, which in the Bjorken limit becomes $x^* \to_{Bj} x/(2 - z_2)$, with $z_2 = [E_2 - p_2 cos(\theta_2)]/M$ being the light-cone momentum fraction of the detected nucleon. Note that any $p_2$-dependent deformation of the nucleon structure function (like, e.g., possible $k_1^2$-dependence) does not produce violations of the spectator scaling property of $F^{(s.i.)}$. In what follows, we will refer to the function $F^{(sp)}(x^*, Q^2, p_2)$ and variable $x^*$, given explicitly by

$$F^{(sp)}(x^*, Q^2, p_2) \equiv M \; p_2 \; n^{(D)}(p_2) \; F_2^{N_1}(x^*, Q^2) \; / \; x^* \tag{8}$$

$$x^* \equiv \frac{Q^2}{Q^2 + (\nu + M_D - E_2)^2 - (\vec{q} - \vec{p}_2)^2 - M^2} \tag{9}$$

as the spectator-scaling function and variable, respectively. The essence of the spectator scaling relies on the fact that the variable $x^*$ implies different electron and nucleon kinematical conditions (in $x$ and $\theta_2$), which correspond to the same value of the invariant mass produced on the struck nucleon. Therefore, the deuteron response will be the same only if the spectator mechanism dominates. Indeed, the spectator scaling is a peculiar feature of the spectator mechanism and, therefore, its experimental observation represents a test of the dominance of the spectator mechanism itself.

An obvious question is whether an approximate spectator-scaling holds at moderate values of $Q^2$ ($\sim$ few $(GeV/c)^2$), i.e. in a range of values of $Q^2$ which can be reached, e.g., at $CEBAF$. To this end, the semi-inclusive cross section (1) for the process $^2H(e, e'p)X$ has been calculated using Eqs. (2,4) and assuming $E_e = 6\ GeV$, $Q^2 = 4\ (GeV/c)^2$ and $p_2 = 0.1,\ 0.3,\ 0.5\ GeV/c$. The Bjorken variable $x$ and the nucleon detection angle $\theta_2$ have been varied in the range $0.35 \div 0.95$ and $10^o \div 150^o$, respectively (for sake of simplicity, the polar angle $\phi_2$ has been chosen equal to 0). As for the nucleon structure function, the parametrization of the $SLAC$ data of Ref. [2], containing both the $DIS$ and nucleon resonance contributions, has been adopted. The results of the calculations are shown in Fig. 1 and compared with the spectator-scaling function (8). It can clearly be seen that the spectator scaling is almost completely fulfilled at $p_2 \simeq 0.1\ GeV/c$, whereas spectator-scaling violations are relevant already at $p_2 = 0.5\ GeV/c$, preventing the nucleon resonance peaks to be observed. This result is due to the $\vec{p}_2$-dependence of the coefficients $C_i^2$ (see Eq. (4)), produced mainly by the convective part of the electromagnetic current (note that at $\vec{p}_2 = 0$ one has $D^{N_1}(x, Q^2; \vec{p}_2 = 0) = 1$). The results obtained for the quantity $D^n(x, Q^2; \vec{p}_2)$ (Eq. (7)), which represents the ratio $F^{(s.i.)}(x, Q^2, \vec{p}_2)/F^{(sp)}(x^*, Q^2, p_2)$, are reported in Figs. 2a and 2b for forward ($\theta_2 < 90^o$) and backward ($\theta_2 > 90^o$) proton emission, respectively. Moreover, the effects on $D^n(x, Q^2; \vec{p}_2)$ due to different off-shell prescriptions for the nucleonic tensor $W_{\mu\nu}^{N_1, off}$ have been investigated. In Fig. 2 the open squares are the results of the calculations performed following the prescription of Ref. [8], according to which in the nucleonic tensor (3) $k_1^{off}$ is replaced by $k_1^{on} \equiv (\sqrt{M^2 + |\vec{k}_1|^2}, \vec{k}_1) = (E_2, -\vec{p}_2)$ and the four-momentum transfer $q = (\nu, \vec{q})$ by $\bar{q} = (\bar{\nu}, \vec{q})$ with $\bar{\nu} = \nu + k_{1,0}^{off} - k_{1,0}^{on} = M_D - 2E_2$. The following comments are in order: i) the limiting value $D^n = 1$ is reached within $\sim 20\%$; ii) spectator scaling violations at $Q^2 = 4\ (GeV/c)^2$ are $\sim 15\%$ in case of forward proton emission and only within $\sim 5\%$ for backward proton kinematics, thanks to the $cos(\theta_2)$-dependence of the coefficients $C_L^2$ and $C_{LT}^2$; iii) at low values of $p_2$ ($\lesssim 0.3\ GeV/c$) the effects due to different off-shell prescriptions for the nucleonic tensor turns out to be quite small (cf. also [9]).

In the spectator-scaling regime the measurement of the semi-inclusive cross section both for $^2H(e, e'p)X$ and $^2H(e, e'n)X$ processes would allow the investigation of two spectator-scaling functions, involving the same nuclear part, $Mp_2n^{(D)}(p_2)$, and the neutron and proton structure functions, respectively. Therefore, assuming $R_{L/T}^n = R_{L/T}^p$ (as it is suggested by recent $SLAC$ data analyses [10]), both the nuclear part and the factor $D^{N_1}(x, Q^2; \vec{p}_2)$ cancel out in the ratio of the semi-inclusive cross sections $R^{(s.i.)}(x, Q^2, \vec{p}_2) \equiv d^4\sigma[^2H(e, e'p)X]/ d^4\sigma[^2H(e, e'n)X]$, which provides in this way directly the neutron to proton structure function ratio $R^{(n/p)}(x^*, Q^2)$. It follows that, with respect to the function $F^{(s.i.)}(x, Q^2, \vec{p}_2)$, the ratio $R^{(s.i.)}(x, Q^2, \vec{p}_2)$ exhibits a more general scaling property, for at fixed $Q^2$ it does not depend separately upon $x$, $p_2$ and $\theta_2$, but only on $x^*$. This means that any $p_2$-dependence of the ratio $R^{(s.i.)}$ would allow to investigate off-shell deformations of the nucleon structure functions (see below).

The results presented and, in particular, the spectator-scaling properties of $F^{(s.i.)}$ and $R^{(s.i.)}$ could in principle be modified by the effects of mechanisms different from the spectator one, like, e.g., the fragmentation of the struck nucleon, or by the breakdown of the impulse approximation (2). In order to estimate the effects of the so-called target fragmentation of the struck nucleon (which is thought to be responsible for the production of slow hadrons in $DIS$ processes), we make use of the same approach already applied in Ref. [11] for investigating the nucleon emission in semi-inclusive $DIS$ of leptons off light and complex nuclei. In [11] the hadronization mechanism is parametrized through the use of fragmentation functions, whose explicit form has been chosen according to the prescription of Ref. [12], elaborated to describe the production of slow protons in $DIS$ of (anti)neutrinos off hydrogen and deuterium targets. Furthermore, the effects arising from possible six-quark ($6q$) cluster configurations at short internucleon separations, are explicitly considered. According to the mechanism first proposed in Ref. [13], after lepton interaction with a quark belonging to a $6q$ cluster, nucleons can be formed out of the penta-quark residuum and emitted forward as well as backward. The details of the calculations can be easily inferred from Ref. [14], where $6q$ bag effects in semi-inclusive $DIS$ of leptons off light and complex nuclei have been investigated. The estimate of the nucleon production, arising from the above-mentioned target fragmentation processes, is shown in Fig. 3 for the function $F^{(s.i.)}$ and in Fig. 4 for the ratio $R^{(s.i.)}$. It can clearly be seen that: i) only at $x^* \lesssim 0.4$ the fragmentation processes can produce relevant violations of the spectator scaling (see Figs. 3 and 4(a)); ii) backward kinematics (see Fig. 4(b)) appear to be the most appropriate conditions to extract the neutron to proton ratio $R^{(n/p)}$. These results are not unexpected, because i) fragmentation processes produce only forward nucleons in a frame where the struck nucleon is initially at rest, and ii) target fragmentation is mainly associated with a diquark remnant carrying a light-cone momentum fraction $\sim (1 - x^*)$, which vanishes as $x^* \rightarrow 1$ (cf. also [11, 14]). Moreover, explicit calculations show that the relevance of the fragmentation processes drastically decreases when $p_2 < 0.5\ GeV/c$.

As far as the impulse approximation is concerned, it should be reminded that our calculations have been performed within the assumption that the debris produced by the fragmentation of the struck nucleon does not interact with the recoiling spectator nucleon. Estimates of the final state interactions of the fragments in semi-inclusive processes off the deuteron have been obtained in [15], suggesting that rescattering effects should play a minor role thanks to the finite formation time of the dressed hadrons. Moreover, backward nucleon emission is not expected to be sensitively affected by forward-produced hadrons (see [16]).

Besides fragmentation and final state interaction, also nucleon off-shell effects might produce violations of the spectator scaling, in particular at high values of $p_2$ ($\gtrsim 0.3\ GeV/c$). The results of the calculations of the ratio $R^{(s.i.)}(x, Q^2, \vec{p}_2)$, obtained considering the off-shell effects suggested in Refs. [17][b] and [8], are shown in Fig. 5(a) and 5(b), respectively. It can

[b] In [17] a $Q^2$-rescaling model, based on a rescaling parameter related to the virtuality $k_1^2 = (M_D - E_2)^2 - p_2^2$

be concluded that the measurement of the ratio $R^{(s.i.)}(x, Q^2, \vec{p}_2)$ represents an interesting tool both to investigate the ratio of free neutron to proton structure function, provided $p_2 \sim 0.1 \div 0.2\ GeV/c$, and to get information on possible off-shell behaviour of the nucleon structure function when $p_2 \gtrsim 0.3\ GeV/c$.

Before closing, we want to address briefly the question whether semi-inclusive processes off complex nuclei exhibit the spectator-scaling property. A detailed analysis is in progress; here, we want only to mention that the results previously obtained in case of the process $^2H(e,e'N)X$ can be easily generalized to reactions of the type $A(e,e'(A-1)_{gr})X$, in which, besides the scattered electron, the residual $(A-1)$-nucleon system in its ground state (or in any state belonging to its discrete spectrum) is detected in the final state. For these processes the spectator-scaling function and variable are explicitly given by

$$\begin{aligned} F^{(sp)}(x^*, Q^2, k_{A-1}) &= \frac{M\ k_{A-1}\ E_{A-1}\ n^{(gr)}(k_{A-1})}{\sqrt{M^2 + k_{A-1}^2}} \frac{F_2^N(x^*, Q^2)}{x^*} \\ x^* &\equiv \frac{Q^2}{Q^2 + (\nu + M_A - \sqrt{M_{A-1}^2 + k_{A-1}^2})^2 - (\vec{q} - \vec{k}_{A-1})^2 - M^2} \end{aligned} \tag{10}$$

where $N$ is the missing nucleon, $\vec{k}_{A-1}$ the momentum of the detected nucleus $(A-1)$, $E_{A-1} = \sqrt{M_{A-1}^2 + k_{A-1}^2}$ its total energy and $n^{(gr)}(k)$ the nucleon momentum distribution corresponding to the ground-to-ground transition. Note that, in case of $A > 2$, no nucleon fragmentation process can be in competition with the spectator mechanism.

In conclusion, the production of slow nucleons in semi-inclusive deep inelastic electron scattering off the deuteron has been investigated in the kinematical regions corresponding to $x \gtrsim 0.3$. It has been shown that within the spectator mechanism the semi-inclusive cross section exhibits an interesting scaling property even at moderate values of $Q^2$ ($\sim$ few $(GeV/c)^2$) accessible at present facilities, like, e.g., *CEBAF*. It has been pointed out that the spectator scaling can be used as a model-independent test of the dominance of the spectator mechanism itself and allows the investigation of the neutron structure function from semi-inclusive data. In the spectator-scaling regime the neutron to proton structure function ratio can be obtained directly from the ratio of the semi-inclusive cross sections of the processes $^2H(e,e'p)X$ and $^2H(e,e'n)X$. Finally, the spectator-scaling property can be easily generalized to semi-inclusive processes off complex nuclei of the type $A(e,e'(A-1)_{gr})X$, where the residual $(A-1)$-nucleon system in its ground state is detected in the final state.

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## Figure Captions

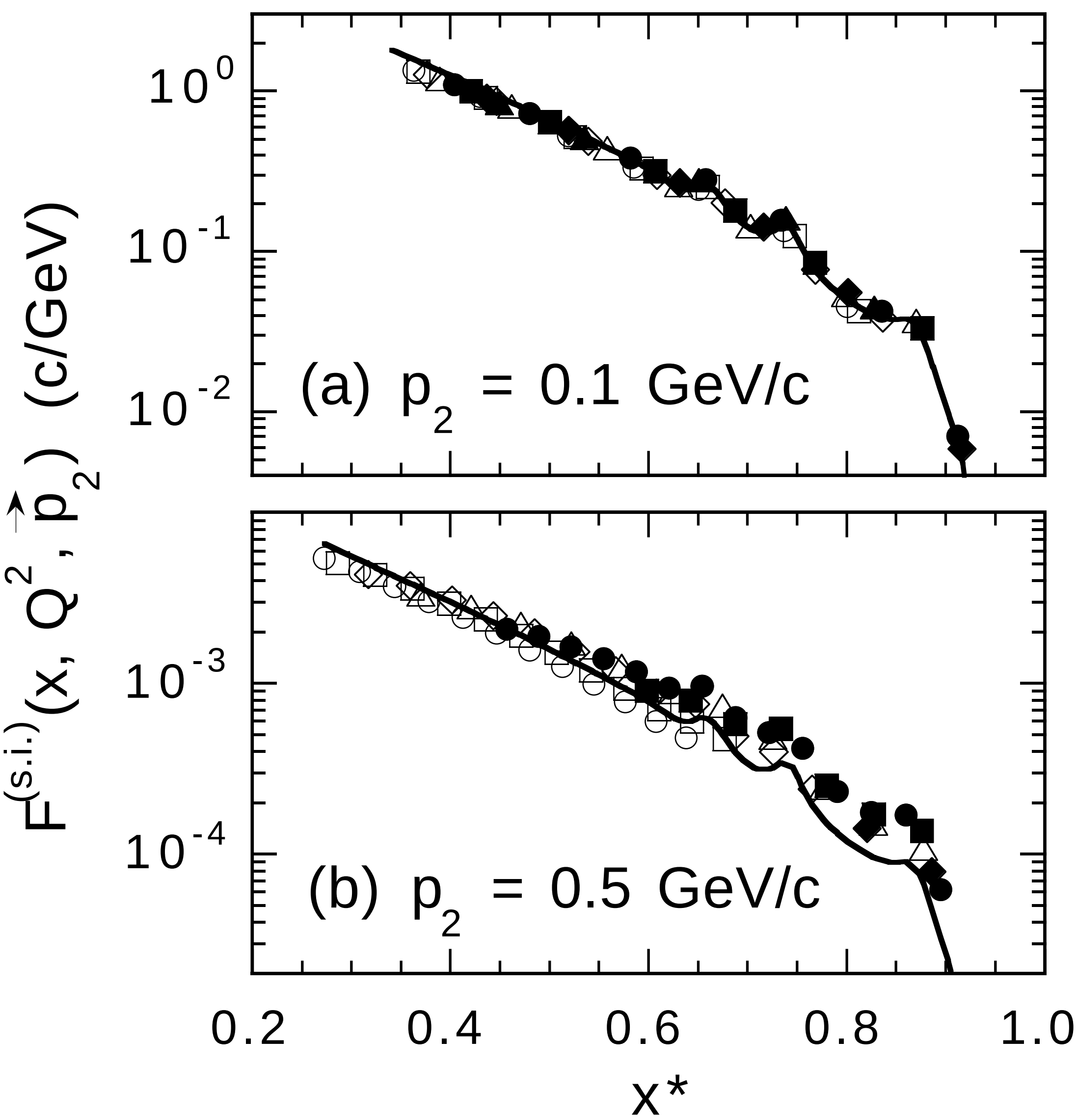
Fig. 1. (a) The function $F^{(s.i.)}(x, Q^2, \vec{p}_2)$ (Eq. (5)) for the process $^2H(e,e'p)X$ plotted versus the spectator-scaling variable $x^*$ (Eq. (9)) at $Q^2 = 4\ (GeV/c)^2$ and $p_2 = 0.1\ GeV/c$. The calculation of the semi-inlcusive cross section (1) is based on the spectator mechanism (see Eqs. (2,4)), assuming the prescription (3) for the off-shell nucleonic tensor. The values of $x$ have been varied in the range $0.35 \div 0.95$. The open (full) dots, squares, diamonds and triangles correspond to $\theta_2 = 10^o$ ($100^o$), $30^o$ ($110^o$), $50^o$ ($130^o$), $70^o$ ($150^o$), respectively. The solid line is the spectator-scaling function $F^{(sp)}(x^*, Q^2, p_2)$ (Eq. (8)) calculated using the deuteron momentum distribution corresponding to the Paris nucleon-nucleon interaction [7] and to the parametrization of the neutron structure function of Ref. [2]. (b) The same as in (a), but at $p_2 = 0.5\ GeV/c$.

Fig. 2. The quantity $D^n(x, Q^2, \vec{p}_2)$ (Eq. (7)) for the process $^2H(e,e'p)X$ plotted versus the spectator-scaling variable $x^*$ (Eq. (9)) at $Q^2 = 4\ (GeV/c)^2$ and $p_2 = 0.1\ GeV/c$. The values of $x$ and $\theta_2$ are the same as in Fig. 1. Forward ($\theta_2 < 90^o$) and backward ($\theta_2 > 90^o$) proton emission are shown in (a) and (b), respectively. The full dots correspond to the results of the calculations based on Eq. (3) for the off-shell nucleonic tensor, whereas the open squares are the results obtained following the off-shell prescription of Ref. [8].

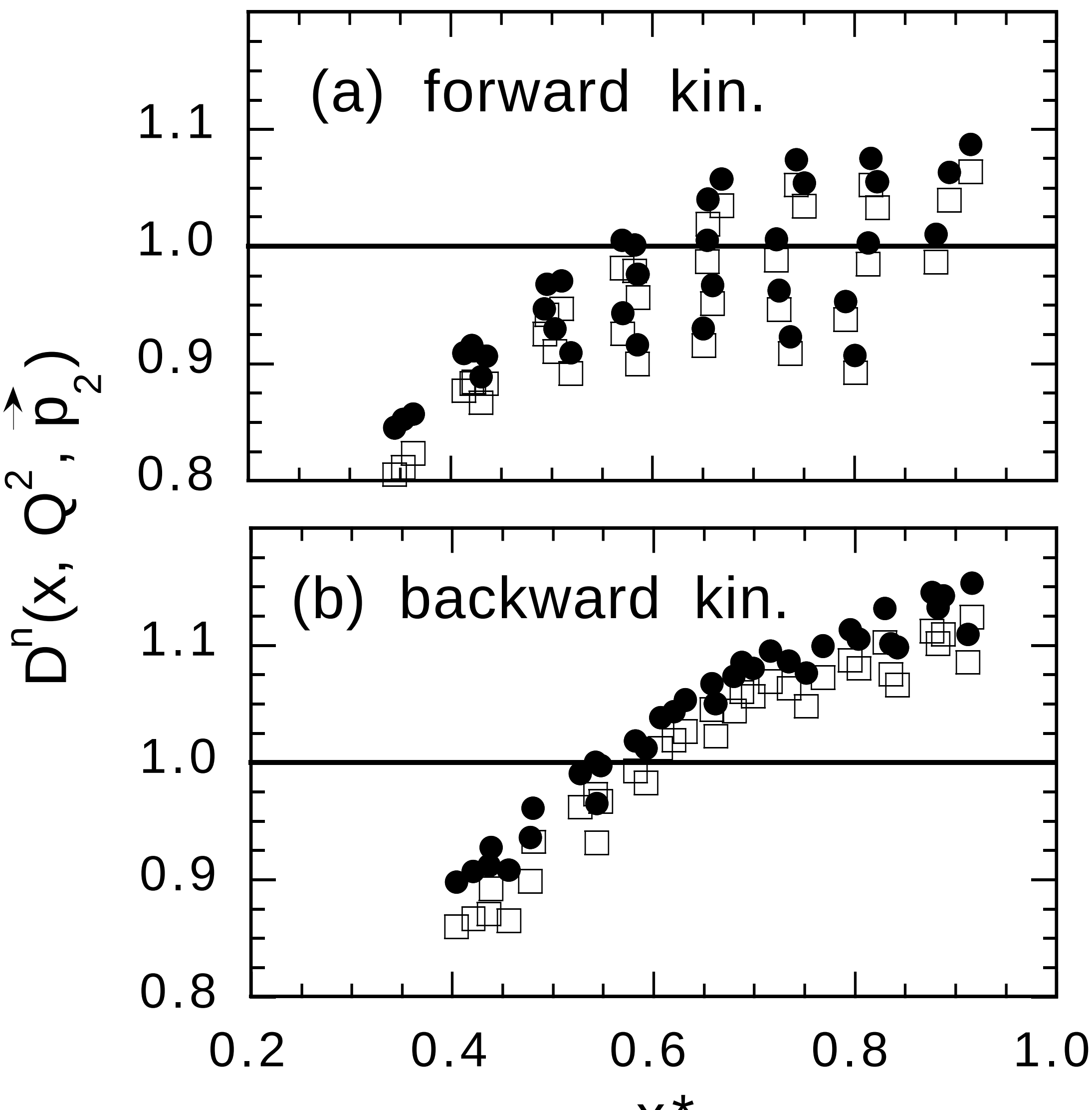
Fig. 3. The quantity $F^{(s.i.)}(x, Q^2, \vec{p}_2)$ (Eq. (5)) for the process $^2H(e,e'p)X$ plotted versus the spectator-scaling variable $x^*$ (Eq. (9)) at $Q^2 = 4\ (GeV/c)^2$ and $p_2 = 0.5\ GeV/c$. The calculations include the effects of the target fragmentation of the struck nucleon, evaluated as in Ref. [11], as well as the contribution of the proton emission arising from virtual photon absorption on a $6q$ cluster configuration in the deuteron, evaluated following Ref. [14] and adopting a $6q$ bag probability equal to 2%. The values of $x$ and $\theta_2$, as well as the solid line, are the same as in Fig. 1(b).

Fig. 4. (a) The ratio $R^{(s.i.)}(x, Q^2, \vec{p}_2)$ of the semi-inclusive cross sections (1) for the processes $^2H(e,e'p)X$ and $^2H(e,e'n)X$, calculated at $Q^2 = 4\ (GeV/c)^2$ and $x$ in the range $0.35 \div 0.95$. The full (open) dots, squares, diamonds and triangles correspond to $p_2 = 0.3\ (0.5)\ GeV/c$ and $\theta_2 = 10^o, 30^o, 50^o, 70^o$, respectively. The results obtained at $p_2 = 0.1\ GeV/c$ and $\theta_2 = 10^o, 30^o, 50^o, 70^o$ are represented by the crosses, plus signs, full and open (downward) triangles, respectively. The solid line is the neutron to proton structure function ratio $R^{(n/p)}(x^*, Q^2)$ calculated using the parametrization of the nucleon structure function of Ref. [2], which predicts a (model-dependent) limiting value of $\sim 0.35$ at $x^* \to 1$ and $Q^2 = 4\ (GeV/c)^2$. (b) The same as in (a), but for backward nucleon emission at $\theta_2 = 100^o, 110^o, 130^o, 150^o$.

Fig. 5. The ratio $R^{(s.i.)}(x, Q^2, \vec{p}_2)$ of the semi-inclusive cross sections for the processes $^2H(e,e'p)X$ and $^2H(e,e'n)X$, calculated considering the off-shell effects proposed in Refs. [17] (a) and [8] (b), respectively. Backward nucleon emission only ($\theta_2 > 90^o$) has been considered. The dots, squares and triangles correspond to $p_2 = 0.1,\ 0.3,\ 0.5\ GeV/c$, respectively. The solid line is the same as in Fig. 4.




S. Simula, Phys. Lett. B: fig. 1

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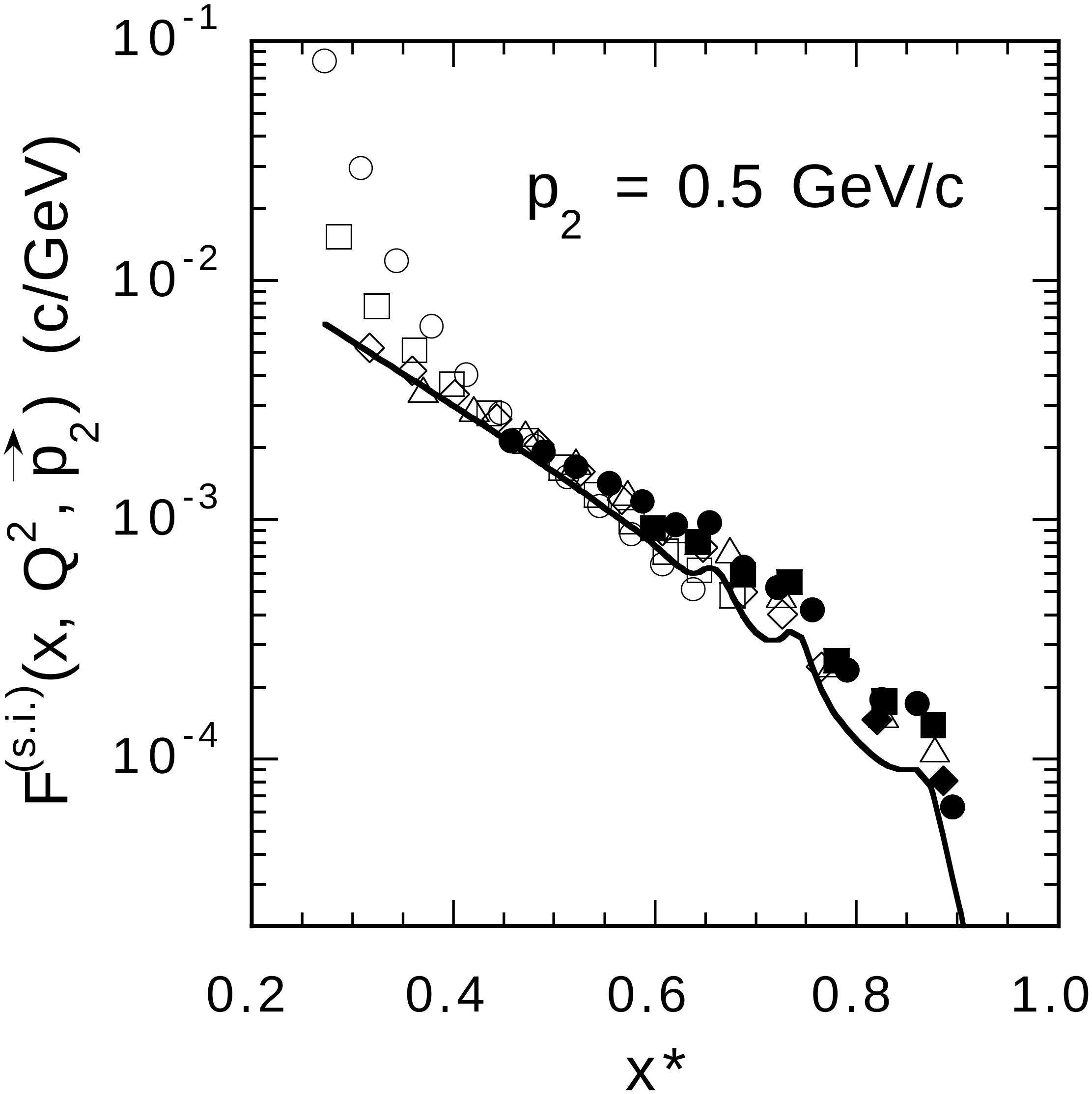
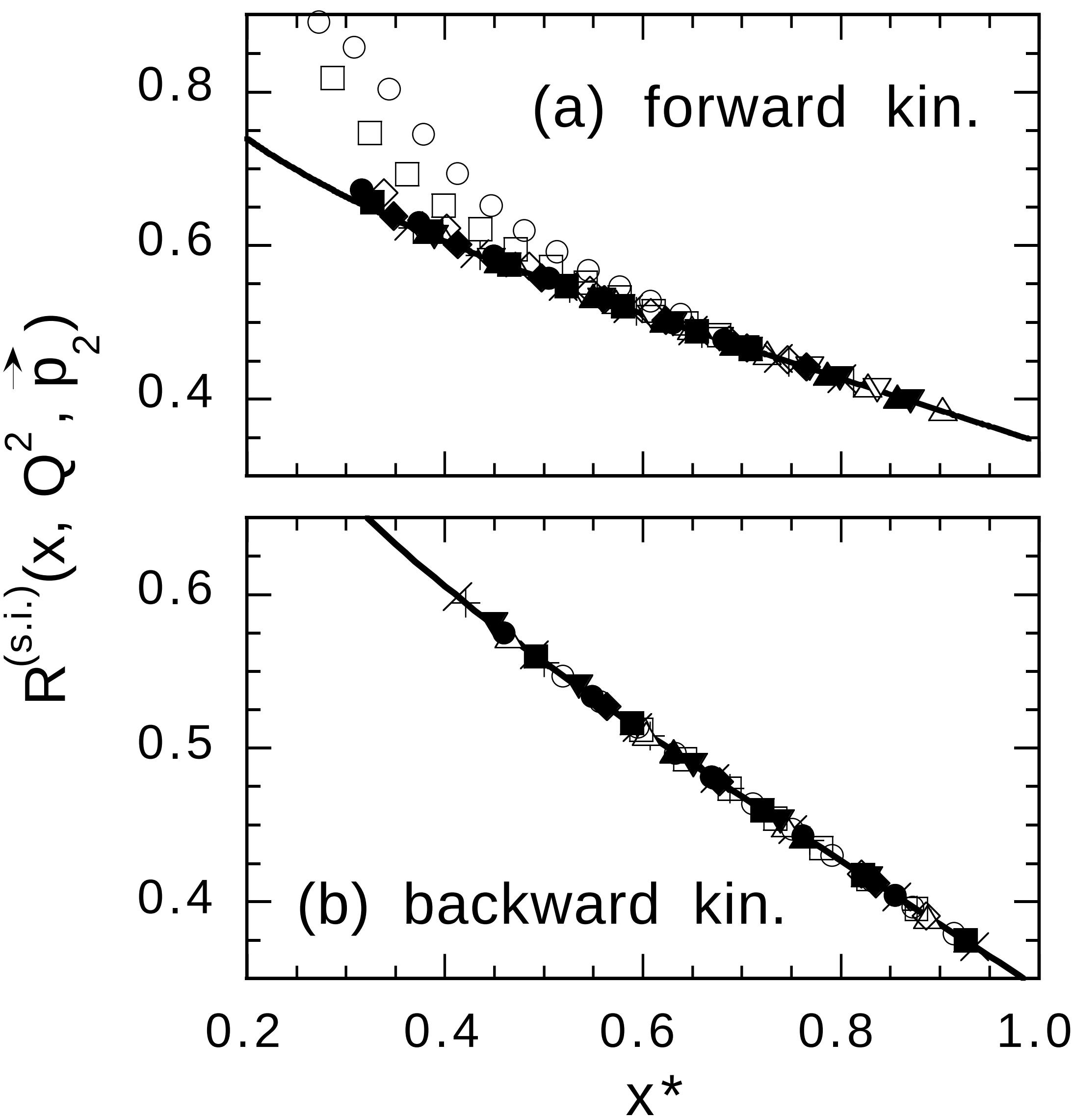
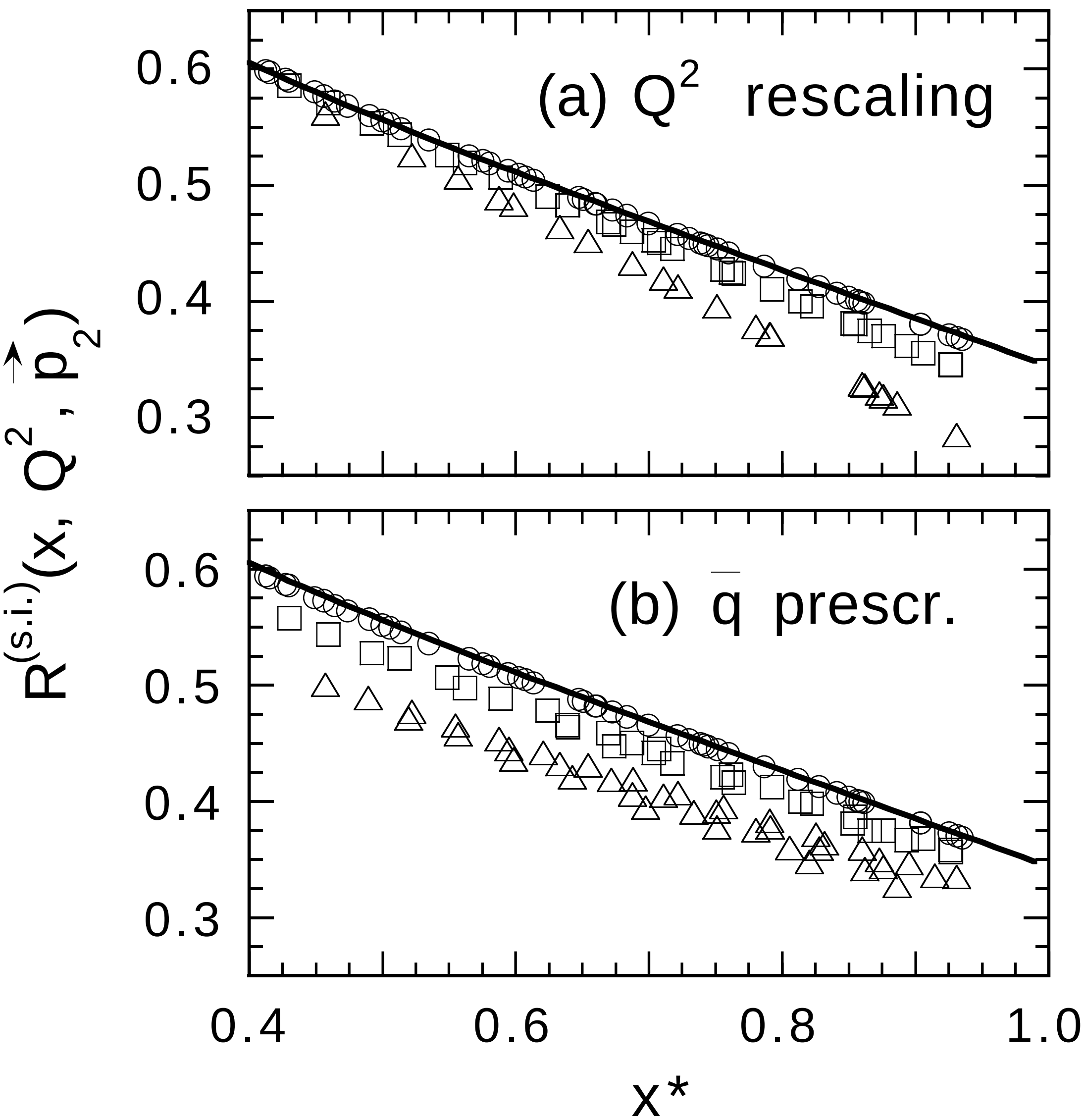



S. Simula, Phys. Lett. B: fig. 3




S. Simula, Phys. Lett. B: fig. 4




S. Simula, Phys. Lett. B: fig. 5